Research Report

DOSIMETRIC EVALUATION OF THE ALPHA

FLUX IN SOLAR PARTICLE BEAMS

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SUMMARY PAGE

THE PROBLEM

Recordings of flare produced particle beams during the past solar maximum indicate that alpha particles are a regular constituent of the flux, sometimes reaching, in the rigidity spectrum, an abundance ratio of one to one to the proton component. It seems of interest to evaluate, for this flux ratio, a typical flare spectrum with regard to absorbed tissue doses and dose equivalents behind various shield configurations.

FINDINGS

A one to one flux ratio in the rigidity spectrum of the incident radiation corresponds to a substantially smaller alpha to proton flux ratio in terms of the range spectrum and this ratio becomes progressively smaller with increasing depth in shield or tissue. Evaluation of the depth dose distributions for a parallel beam and for the compound shield system of the Apollo vehicle using the rigidity spectrum of the 1956 flare shows that the total absorbed dose of the alpha component is, at all depths, smaller than the proton dose. Very differently, the fractional high LET alpha dose is substantially larger than the fractional proton dose and intersects the latter only at a depth greater than 12 g/cm^2.

Applying the Quality Factor (QF) and Relative Biological Effectiveness (RBE) values of the RBE Committee to the ICRP to the data furnishes the depth distributions of the mean local QF and RBE. For the alpha component analyzed separately, a QF of 2.6 is obtained in the tissue surface behind 2 g/cm^2 shielding, dropping gradually to 1.5 at 20 g/cm^2 depth in tissue. In the combined exposure from both components, however, the proton contribution lowers the corresponding QF values to 1.8 and 1.2, respectively.

The findings indicate that the alpha component of flare beams poses a problem only for cases of low shielding. It almost matches the proton dose in the surface of a tissue target behind 2 g/cm^2 shielding, but drops much more steeply than the proton dose with increasing depth. For very low shielding, the alpha dose is the predominant contributor to exposure in the surface layers of a human target.

INTRODUCTION

Concern has been expressed recently by various investigators lest the alpha component in solar particle beams might constitute a major addition to the exposure from protons. Especially the conclusion drawn by Freier and Webber (1) from a synoptic evaluation of several large flares of the past solar maximum that some solar particle beams show rigidity spectra with a one to one flux ratio of protons to alpha particles is being invoked as proof that considering the proton component alone underestimates the radiation exposure substantially. From measurements in satellites and space probes as well as from theoretical analyses of the transition of solar proton beams in shielding material it has become abundantly clear that the "air" dose of the incident beam is disproportionately larger than the absorbed dose in a human target inside a ship. From the general physical characteristics of alpha particles one would suspect that this difference between the free space dose and the tissue dose inside a vehicle will even be larger than for protons. On the other hand, alpha particles have a much higher Linear Energy Transfer (LET) in the terminal sections of their paths. Therefore, they can be expected to dissipate a substantially larger fraction of their total energy in tissue at LET values which would require factors of Relative Biological Effectiveness (RBE) larger than 1.0 in assessing rem dose equivalents.

The foregoing remarks indicate the need for a quantitative analysis of the depth of penetration of the proton and alpha components of solar particle beams in order to determine residual doses behind representative shield configurations. The present report is an attempt in this direction. It reviews the LET/energy and range/energy relationships for protons and alpha particles and applies them to the rigidity spectrum of a maximum type flare event assuming a one to one flux of the two components. For a complete dosimetric evaluation, four separate doses are determined: the total absorbed dose for protons, the same dose for alpha particles, the fractional high LET dose for protons, and the same dose for alpha particles.

Certain difficulties arise if high LET doses are to be converted from rad to rem values. Official recommendations of the International Commission on Radiological Protection (2) specify Quality Factor (QF) values only up to an LET of 100 kev/micron tissue and RBE values only up to 175 kev/micron tissue. Since alpha particles have a maximum LET of 240 kev/micron tissue in the Bragg peak at 0.8 Mev kinetic energy, a substantial part of the high LET dose fraction cannot be readily expressed in terms of QF or RBE dose equivalents. The corresponding problem does not exist for protons. In the Bragg peak at 45 kev kinetic energy they reach only a maximum LET of 87 kev/micron tissue, which is a value well below the upper limits for which official regulations define specific QF and RBE values. Tentative ways of how QF and RBE factors could be extrapolated to 240 kev/micron tissue are discussed in Section III.

I. THE LET/ENERGY RELATIONSHIP FOR ALPHA PARTICLES

The dependence of LET on kinetic energy for alpha particles in tissue has never been measured directly. However, the mechanism of energy dissipation of charged particles in absorbers is well enough investigated experimentally and theoretically to allow interpolation from known LET/E functions for elements of appropriate Z-numbers. Table I* shows the average atomic composition of the human body. For the present purpose it seems entirely acceptable to consider only the four most abundant constituents: oxygen, carbon, hydrogen, and nitrogen. Combining oxygen, carbon, and nitrogen with their closely similar Z-numbers to one substance with a weighted mean Z of 7.3 leads to a further simplified model for tissue as containing 90 per cent of a compound with a Z = 7.3 and 10 per cent hydrogen with a Z = 1. Finally, since air has a mean Z of 7.2, one can substitute air with sufficient accuracy for the compound of Z = 7.3. In other words, the LET for tissue can be determined from the respective LET values for air and hydrogen by assuming density 1.0 and concentrations of 90 per cent and 10 per cent, respectively.

Since interest in the present investigation rests on a comparative analysis of the proton and alpha components, it seems preferable, for consistency, to compile the LET/energy relationship for protons from available experimental data and to base the corresponding relationship for alpha particles on the one for protons by applying the general law that the LET of ionizing particles of the same speed is proportional to the squares of their charges and independent of all other parameters. Since alpha particles consist of four mass units as compared to one for protons, they have four times the kinetic energy at the same speed. Since, furthermore, the squares of the respective charges of alpha particles and protons also have the ratio four to one, it is seen that any pair of LET/E values holding for a proton directly defines a 4LET/4E pair of values for an alpha particle. This rule is valid for all nonrelativistic energies except for the terminal part of the energy scale below 2 Mev kinetic energy for alpha particles. Below that critical energy, the alpha particle starts capturing its orbital electrons, and this results in a progressive diminishing of the effective charge toward lower energies. Table II based on data compiled by Marion (3) lists the ratio of the squares of the effective charges alpha to proton as a function of alpha kinetic energy. In deriving the LET of alpha particles in the energy interval in question from that of protons by applying the aforementioned LET/E-4LET/4E relationship, the factor 4 for the LET has to be replaced by factors to be taken from Table II.

Finally, at very low energies below the Bragg peak, the mechanism of energy dissipation, or more specifically, the relative shares of excitation and ionization are

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*In order not to break the continuity of the text, all tables and figures appear at the end of the report.

not well known, and the role of nuclear interactions is incompletely understood. Therefore, the steep descent of the LET below the Bragg peak is largely conjectural. However, the energy dissipated in this particular track section accounts only for a few per cent of the total high LET dose fraction. Therefore, no significant error is introduced into the analysis by this uncertainty.

Applying the just-outlined procedure to the range/energy relationships for protons in hydrogen and air as communicated by Bethe and Ashkin (4), one obtains the LET/E function for alpha particles in tissue shown in Figure 1. For more accurate computational work, the function is also tabulated in Table III. It should be realized that LET is usually determined as the differential quotient dE/dR from the range/energy function which means that the steep maximum of the LET in the Bragg peak is defined experimentally merely as a point of inflection in a curve of otherwise monotonic slope. That means that the critical slope determining the absolute value of the LET maximum is not measured directly, but can only be interpolated from adjacent range/energy points or determined geometrically from a graph of the range/energy function. As a consequence, even a very accurately measured range/energy function yields the maximum LET only with a certain margin of error. The data of Bethe and Ashkin (l.c., 4) used in the present investigation lead to a maximum LET of 87 kev/micron tissue for protons in the Bragg peak. A slightly higher value of 94 kev/micron tissue has been communicated by Rossi, Bateman, Bond, Goodman, and Stickley (5).

Applying the aforementioned theoretical method to the proton range/energy data of Bethe and Ashkin furnishes corresponding data for alpha particles which indicate a maximum of 240 kev/micron tissue at 0.8 Mev kinetic energy for alpha particles. Lea, in his classical monograph (6), directly lists LET values for alpha particles in tissue in addition to a tabulation of the range/energy function. However, his data cover only the energy range from 10 Mev to 1 Mev. For 1 Mev, Lea lists an LET of 263 kev/micron tissue. Plotting the graph for all ten values indicates that the Bragg peak for Lea's data would occur at an energy slightly below 1 Mev. Since Lea lists a range in tissue of 5.3 micra for 1 Mev, the missing section of the LET graph from 1 Mev to zero can be extrapolated by trial and error applying the test that the definite integral of dE/(LET) over the interval from zero to 1 Mev must equal 5.3 micra. This method leads to a Bragg peak of 275 kev/micron tissue for Lea's data, i.e., to a slightly higher value than the one used in the present investigation. Conceivably, the data of Table II on the gradual decline of effective charge of alpha particles due to capture of orbital electrons were not available when Lea wrote his monograph. This could be responsible for his LET values being too high from 2 Mev on downward. It should be noted that at 0.8 Mev, where the Bragg peak occurs for alpha particles, the square of the effective charge ratio has dropped from 4 to 3.26. In other words, the LET of an alpha particle in the Bragg peak is only 3.26 times larger than the LET of a proton of the same speed.

In conclusion of the discussion of the Bragg peak problem, it might be pointed out that, in the frame of the present study which investigates the ionization dosage

of the alpha component in a human target, the detailed configuration of the Bragg peak is of minor importance. The LET of alpha particles already becomes high in a radiobiological sense at energies between 10 and 20 Mev. In that interval, LET and range in tissue are accurately known. Therefore, the fractional high LET dose in millirads for alpha beams of mixed energy can be determined with any desired accuracy for whatever LET value one would want to select as the critical limit.

II. DEPTH DOSES FROM PROTONS AND ALPHA PARTICLES FOR BAILEY'S FLARE SPECTRUM

In the search for clues on the nature of the acceleration mechanism acting on protons, alpha particles, and heavier nuclei in solar flares, astrophysicists have found it helpful to express observed flux values of flare-emitted charged particles in terms of the magnetic rigidity spectrum. The rigidity of a charged particle is inversely proportional to the radius of curvature of its track in a magnetic field. Rigidity can also be expressed as momentum per unit charge. Rigidity and depth of penetration or range are entirely disparate magnitudes. In comparing protons and alpha particles in particular, the rigidity spectrum is in no way a measure of the residual fluxes behind shields. As alpha particles have two mass units per unit charge and protons only one, equal integral fluxes of the same rigidity represent very different fluxes in terms of momentum or energy or range spectrum. The range spectrum in particular is a very useful description of particle fluxes if problems of shielding and depth doses in a human target are to be analyzed.

The upper graph in Figure 2 shows the integral rigidity spectrum of the particle flux for the giant solar flare of February 23, 1956 established by Bailey (7) on the basis of a synoptic evaluation of all available data on this event. The spectrum exhibits the basic feature of all flare beams that flux steeply drops with increasing rigidity. The lower graph of the same figure shows, over the same rigidity scale as abscissa, the ranges in tissue for protons and alpha particles. It is evident that, for a given rigidity, the corresponding ranges of protons and alpha particles differ greatly. For instance, at 0.6 Bv rigidity an alpha particle has a range of 2 g/cm^2 and a proton of almost 24 g/cm^2. This demonstrates well that space radiation data should be presented in terms of the differential or integral range spectrum rather than in terms of the energy or rigidity spectrum (8) if residual radiation levels behind shielding layers are to be evaluated. Figure 3 shows the rigidity spectrum of the upper graph of Figure 2 converted into differential range spectra. It is seen that the spectrum splits up into two different graphs, one for protons and one for alpha particles. However, this actually simplifies the analysis because the range spectra allow direct comparisons of fluxes that would reach the same depth in tissue or shielding material. It is interesting to see that, for low and very low shielding, the alpha flux drops much more steeply toward greater depths than the proton flux. This indicates that possible objectionable exposures from flare produced alpha particles can occur only for low shielding, as for instance for an astronaut outside the vehicle protected merely by his space suit. To demonstrate

this conclusion quantitatively, flux values have to be evaluated in terms of local dose rates.

The geometry of exposure to solar particle beams in actual space systems is always very intricate since the radiation is incident from all directions on a human target behind a highly complex shield configuration. For the purpose of dose computations, these systems are usually broken down into a large, but finite number of elementary solid angles which can be treated individually as subsystems of constant shield thickness traversed by a parallel beam of normal incidence. The depth dose distribution as it would develop in such a system of simple geometry from a parallel beam with the differential range spectra of the proton and alpha components shown in Figure 3 is plotted in Figure 4. Since the local flux at any depth contains particles of all energies from zero to very high values, the local ionization dose is produced at LET values covering a similarly wide range from very high to low values. Therefore, a complete dosimetric evaluation would call for separate determination of the high LET fraction of the total ionization dose to which RBE factors larger than 1.0 would have to be assigned. The determination of doses for the proton and alpha components in Figure 4, therefore, has been carried out separately for both the total absorbed dose and the high LET fraction of it. The upper graph shows total doses and the lower one fractional doses produced at LET values of 40 kev/micron tissue and higher. A comparison of the total doses from protons and alpha particles shows that, even at the lowest depth of 1.75 g/cm^2, the contribution of the alpha component almost matches the proton dose, but drops much more steeply toward greater depths. However, in extrapolating the graphs toward the left to shield thicknesses below 1.75 g/cm^2 one suspects that for low and very low shielding the situation might become quite different with the alpha dose becoming larger than the proton dose. Actual computation of doses below 1.75 g/cm^2 has not been carried out because the spectral section of the incident beam which would predominantly be responsible for the absorbed dose in the superficial layers is experimentally not well defined.

We proceed now from the analysis of the depth dose distribution in a plane tissue slab for a parallel beam to the distribution that would develop in a tissue target behind the complex shield configuration of an actual space vehicle. Very detailed data have been communicated by North American Aviation, Inc., for the shielding distribution of the Apollo vehicle. In an earlier report (9) these data have been described and used, in a simplified form, to evaluate the depth dose rates in a 30 cm diameter tissue sphere inside the Apollo vehicle for Bailey's spectrum of flare produced protons. It seems of special interest to supplement these earlier data with the corresponding data for the alpha component under the assumption of a flux ratio alpha to proton of one to one in the same way as was done for a parallel beam in Figure 4. The results of this evaluation are presented in Figure 5. The two upper graphs showing the proton data are identical reproductions of Figure 5 of the earlier study (l.c., 9). Here again, the problematic issue of QF and RBE factors has been avoided by plotting directly enders per gram tissue per second. The conversion of enders per gram tissue to millirads depends on the critical LET limit above which one would want to define the dissipated energy

as high LET dose. The selection of such an LET value of necessity will always be arbitrary within wide limits. Possible choices are 40 or 25 or 10 kev/micron tissue. The kinetic energies corresponding to these LET values determine directly the energy dissipation per ender which, in tum, can easily be expressed in milli- or microrads. The pertinent data for the just-proposed three critical LET values are compiled in Table IV for protons and alpha particles. Caution should be applied if the lowest LET of 10 kev/micron tissue is used in evaluating spectra of steep slope. Since an alpha ender beginning at 10 kev/micron tissue has a range of 0.5 g/cm^2, the variation of flux within an interval of 0.5 g/cm^2 in the differential range spectrum has to be taken into consideration. If this correction is disregarded, the high LET dose fraction is substantially over-rendered.

III. QF AND RBE OF ALPHA PARTICLE BEAMS

In the preceding section, the total ionization dosages and their respective high LET fractions have been analyzed, but no conversion of these fractions to actual QF or RBE dose equivalents has been carried out. On the one hand, the choice of appropriate QF and RBE factors introduces a nonscientific, subjective element into the analysis, and, on the other, officially defined maximum permissible doses are stated exclusively in terms of rem dose equivalents. The best way of giving both circumstances full consideration seems to be treating the QF/RBE issue in a separate section. It is clear, then, that the following discussion has no aspirations of presenting the radiobiological aspects of the problem, but is conducted strictly in terms of the recommendations of the ICRP, more specifically, of the Report of the RBE Committee to that Commission (l.c., 2).

As mentioned in the Introduction, the RBE Committee expressly limits the use of the recommended formulae relating QF and RBE to LET to a maximum LET of 100 kev/micron tissue for the QF and 175 kev/micron tissue for the RBE. Since alpha particles have a maximum LET of 240 kev/micron tissue, a method has to be established to extrapolate QF and RBE factors beyond 100 and 175 kev/micron tissue, respectively. To be sure, such a method, whatever its rationale might be, will always be entirely arbitrary since a number of conflicting lines of reasoning offer themselves. A strong argument in favor of keeping QF and RBE factors low derives from the experimental evidence indicating that, for most reactions of living matter to ionizing radiation, the RBE passes through a maximum at a medium high LET somewhere in the region between 100 and 300 kev/micron tissue. In view of this fact, the use of a straightforward extrapolation of the formulae of the RBE Committee would seem unrealistic. For the QF in particular, this extrapolation would furnish a value of 39.2 for the maximum LET of alpha particles, which is plainly absurd. In the context of the present investigation in particular, where main emphasis rests on the safety of a time limited mission, i.e., on avoidance of acute somatic damage, an additional argument derives from the fact that experimental data consistently indicate that the RBE for producing such damage in mammalian systems is markedly lower than for more subtly local effects such as chromosomal damage in individual cells.

The foregoing few remarks might suffice to indicate the complexity of the issues involved. Without further discussion, we proceed now to present, in Figure 6, the QF/LET and RBE/LET functions used in the following evaluation. The QF curve represents, from 0 to 100 kev/micron tissue, the formula of the RBE Committee. Beyond 100 kev/micron tissue an entirely arbitrary curvilinear extrapolation to the value 20 reached at 240 kev/micron tissue has been chosen. This extrapolation reflects the tenet that a maximum QF of 20 represents a very conservative, i.e., high, estimate for acute somatic effects. The curve for the RBE in Figure 6 also represents the pertinent formula of the RBE Committee. Contrary to the QF curve, the formula in this case is maintained throughout the entire LET interval from 0 to 240 kev/micron tissue. In other words, the formula is used beyond the maximum limit recommended by the Committee. Since the maximum of 12.9 at 240 kev/micron tissue remains well below 20, this extrapolation seems acceptable though some might call it extremely cautious.

In concluding the discussion it should be emphasized once more that the suggested values for the QF beyond 100 kev/micron tissue and for the RBE beyond 175 kev/micron tissue in Figure 6 are those of the author. As existing evidence indicates that alpha beams of mixed energy constitute a definite radiation hazard in space, official permissible rem dose limits will have to be established. Before the appropriate advisory or legislative bodies can officially formulate such limits, the problem needs to be thoroughly debated within the scientific community. The foregoing proposal is intended as a stimulus in this direction.

In applying the QF/LET and RBE/LET relationships of Figure 6 to protons and alpha particles one can evaluate a mean and an instantaneous QF or RBE factor for a given kinetic energy E. The former, the mean factor, would represent a weighted mean for the entire energy dissipation of the particle from E to zero whereas the latter would hold strictly for a small amount of energy dissipated by a particle of energy E. The instaneous QF or RBE factors can be read directly from Figure 6 if the LET/E relationship is known. The mean QF or RBE factors require an additional computation analysis breaking down the energy from zero to E in small intervals, establishing the instantaneous QF or RBE for each interval, and deriving the weighted mean. The results of this evaluation are presented in Figures 7 and 8. A comparison of the respective curves for protons and alpha particles demonstrates that alpha particles not only show higher QF and RBE values, but also sustain them over substantially larger energy intervals.

IV. DEPTH DISTRIBUTION OF LOCAL QF AND LOCAL RBE FOR THE PROTON AND ALPHA COMPONENT OF BAILEY'S FLARE SPECTRUM

Similarly to the just-outlined method of establishing the mean QF and mean RBE for a single particle or monoenergetic beam of given energy E, the mean local QF and RBE can be established for a heterogeneous beam at a given depth in a shield or target absorber by breaking down the local energy spectrum in narrow intervals,

determining the instantaneous QF or RBE for each interval, and computing the mean. It seems of interest to apply this method to the depth dose distribution of the system of Figure 4. The results are presented in Figure 9. A striking difference between the alpha and the proton component is immediately apparent. Whereas QF and RBE for the proton component never greatly depart from 1.0, the corresponding factors for the alpha component remain larger than 1.0 throughout the entire depth of the tissue slab or spherical target. For the combined mean factors comprising the proton and the alpha component, the departure from 1.0 is greatly reduced because the alpha component, due to its smaller ionization dosage, is represented in the mean with a smaller weight than the proton component.

The basic features of the local mean QF and RBE factors are the same for both the parallel beam of normal incidence and the compound shielding system of the Apollo vehicle. For the latter system, QF and RBE factors directly in the surface of the target are slightly smaller than the corresponding values in the tissue slab due to the circumstance that the surface dose in the Apollo system is partly produced by particles which have passed through shield thicknesses much larger than the minimum value of 1.75 g/cm^2. For details on the geometry of the Apollo shield distribution the report of reference 9 should be consulted.

CONCLUSIONS

The foregoing analysis has demonstrated the basic difference between the alpha and proton components of solar particle beams. Evaluated separately, the former was found to dissipate a substantial fraction of the total ionization at high LET values, whereas the latter contains only a fractional high LET dose of a few per cent. However, it is quite obvious that the actual hazard to man depends on the combined exposure from both components. In this respect the most important finding of this analysis is the one presented in Figure 2 demonstrating that the flux values for the alpha component are always substantially smaller than those for the proton component and that this bias increases with increasing thickness or depth in the target. For this reason, the high LET fraction of the total exposure and the corresponding mean QF and RBE factors are predominantly determined by the proton component. In other words, the high fractional rem dose equivalents for the alpha component evaluated separately are only of theoretical interest. In actual exposures to solar particle beams, they show in the total dose only to a moderate degree.

The data of this study have been established for the highest alpha to proton flux ratio reported in the literature. For the majority of flare events much smaller values down to a ratio of 1 to 60 have been measured. Since the acceleration of protons and alpha particles in solar flares as well as in interplanetary magnetic fields seems to be a uniform process for both components, conditions could hardly be conceived which would lead to local development of a particle beam predominantly or exclusively made up of alpha particles. Therefore, rem dose equivalents in solar particle beams will be

substantially higher than rad doses only in systems with low shielding and only in the first 2 or 3 centimeters of depth in a human target. On the other hand, the separate measurement of the high LET dose fraction for the long-term assessment of the exposure status already proposed earlier for the proton component assumes added importance in the light of the nature of the additional exposure from the alpha component.

Finally, with regard to exposure conditions for very low shielding below 1.0 g/cm^2, it should be emphasized once more that the accuracy of spectral data on solar particle beams does not seem sufficient to allow a quantitative analysis. Since the differential alpha flux steeply approaches and probably intersects and surpasses the proton flux at very low shield thicknesses, extrapolation becomes quite unreliable. As direct recordings of fluxes for such low prefiltration for the flares of the past solar maximum are not available, this particular aspect of the problem must remain unexplored for the time being. This has the unfortunate consequence that the flare hazard for an astronaut protected merely by his space suit or in other equivalent circumstances cannot be properly assessed.

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Table I

Average Atomic Composition of the Human Body

Element	Symbol	Atomic Number Z	Per Cent of Total Weight
Oxygen	O	8	65%
Carbon	C	6	18
Hydrogen	H	1	10
Nitrogen	N	7	3
Calcium	Ca	20	1.5
Phosphorus	P	15	1.0
Potassium	K	19	0.35
Sulfur	S	16	0.25
Sodium	Na	11	0.15
Chlorine	Cl	17	0.15
Magnesium	Mg	12	0.05
Iron	Fe	26	0.004
Manganese	Mn	25	0.0003
Copper	Cu	29	0.0002
Iodine	I	53	0.00004

Table II

Ratio of Alpha Particle to Proton Stopping Cross Section*

Alpha Particle Kinetic Energy, Mev	Cross Section Ratio	Alpha Particle Kinetic Energy, Mev	Cross Section Ratio
0.16	1.87	0.80	3.26
0.20	2.02	0.88	3.37
0.24	2.16	0.96	3.46
0.32	2.39	1.12	3.64
0.40	2.57	1.28	3.79
0.48	2.75	1.44	3.95
0.56	2.89	1.60	3.97
0.64	3.03	1.76	4.00
0.72	3.15		

*Data of J. B. Marion; See Reference (3).

Table III

LET of Alpha Particles as a Function of Kinetic Energy

Alpha Particle Kinetic Energy Mev	LET, kev/ micron$_T$	Alpha Particle Kinetic Energy, Mev	LET, kev/ micron$_T$
0	—	8	67.0
0.05	93.0	10	56.3
0.10	135.0	12	49.0
0.15	160.0	14	43.2
0.20	178.0	16	39.0
0.30	202.0	20	32.6
0.40	218.0	25	27.2
0.50	229.0	30	23.4
0.6	236.0	35	20.8
0.7	239.7	40	18.8
0.8	240.6	50	15.8
0.9	240.2	60	13.6
1.0	238.8	80	10.9
1.2	233.0	100	9.07
1.4	224.0	125	7.55
1.6	211.0	150	6.57
2.0	181.0	200	5.23
2.4	158.5	250	4.39
2.8	142.0	300	3.80
3.2	128.5	400	3.02
3.6	118.0	500	2.59
4.0	110.0	600	2.29
5.0	94.2	800	1.90
6.0	82.7	1000	1.64

Note added in proof: From 8 Mev up, LET values for alpha particles are tabulated in the new NASA publication SP - 3013 by W. H. Barkas and M. J. Berger reflecting the best available information. LET values listed above are about 10 per cent larger than the values for muscle tissue in SP - 3013.

Table IV

Conversion of Density of Enders to Absorbed Dose for Selected LET Threshold Values of Protons and Alpha Particles

	LET, kev/ micron tissue	Kinetic Energy, Mev	Range in Tissue, micra	Microrads for 1 Ender/ gram tissue
Protons	10	3.92	284	0.0696
	25	1.15	26	0.0204
	40	0.59	11	0.0105
Alpha Particles	10	89.2	5000	1.583
	25	27.6	700	0.490
	40	15.5	275	0.275

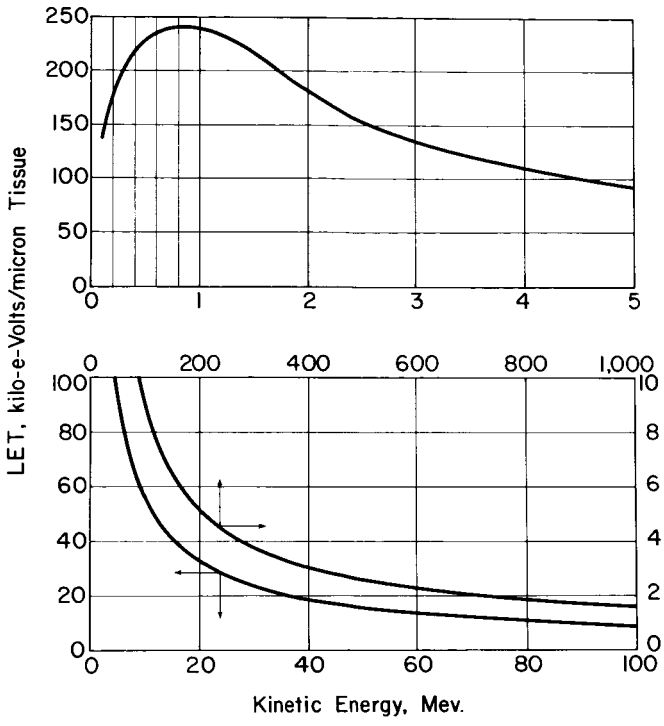

Figure 1

Linear Energy Transfer of Alpha Particles
as a Function of Kinetic Energy

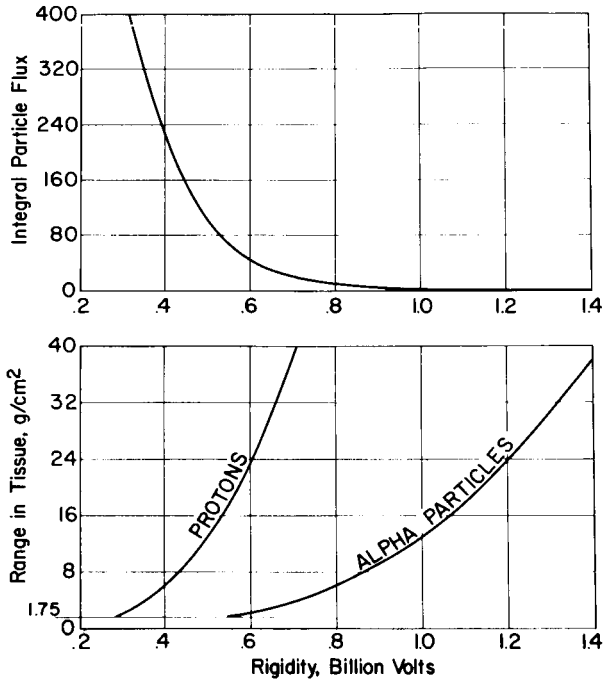

Figure 2

Integral Rigidity Spectrum of Particle Flux
for 1956 Flare and Corresponding Ranges
in Tissue for Protons and Alpha Particles

Ordinate scale of top graph shows protons or alpha particles/ (cm^2 sec sterad).

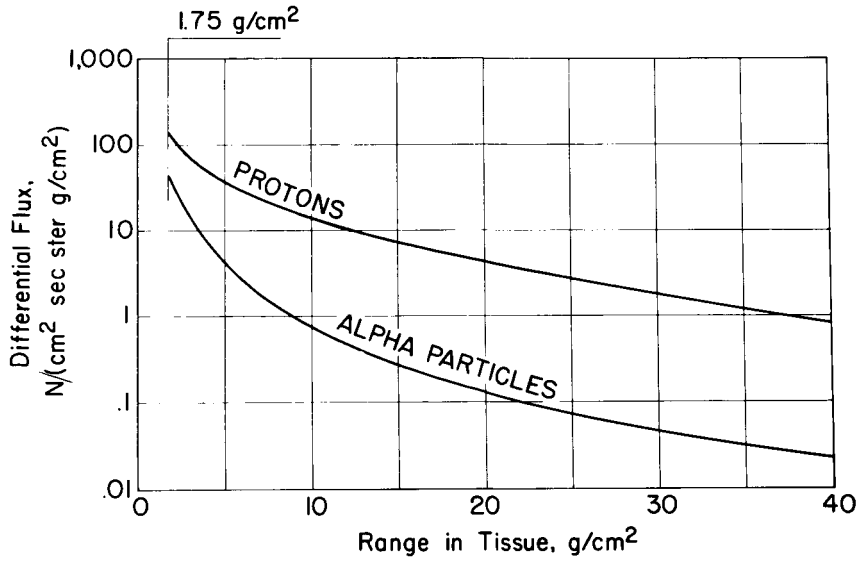

Figure 3

Differential Range Spectra for Protons and Alpha Particles for the Integral Rigidity Spectrum Shown in Top Graph of Figure 2

Note that combined flux of both components would lead to twice the ordinate values in top graph of Figure 2.

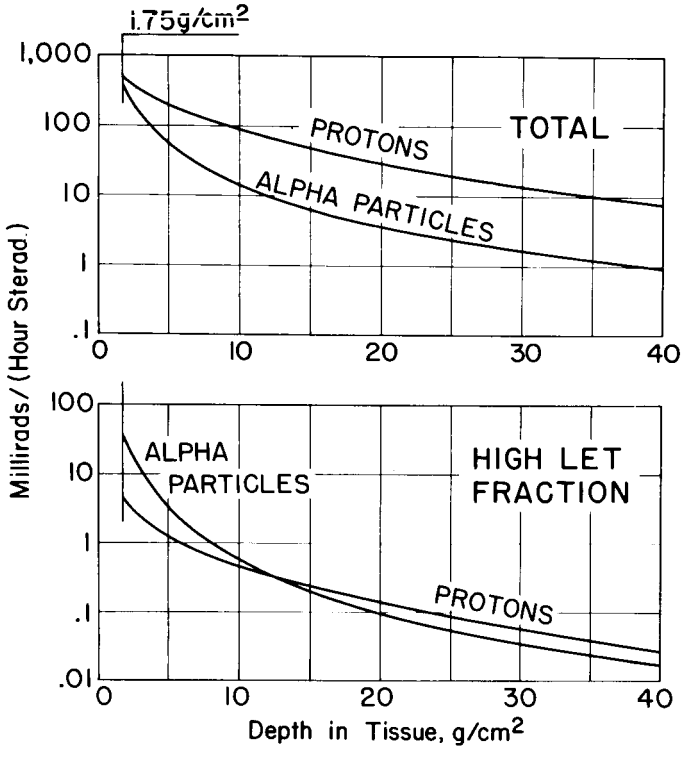

Figure 4

Absorbed Dose in Tissue for Parallel
Beam of Normal Incidence for Proton and
Alpha Spectra Shown in Figure 3

Top: Total absorbed dose; Bottom: Fractional high LET dose for LET > 40 kev/micron tissue.

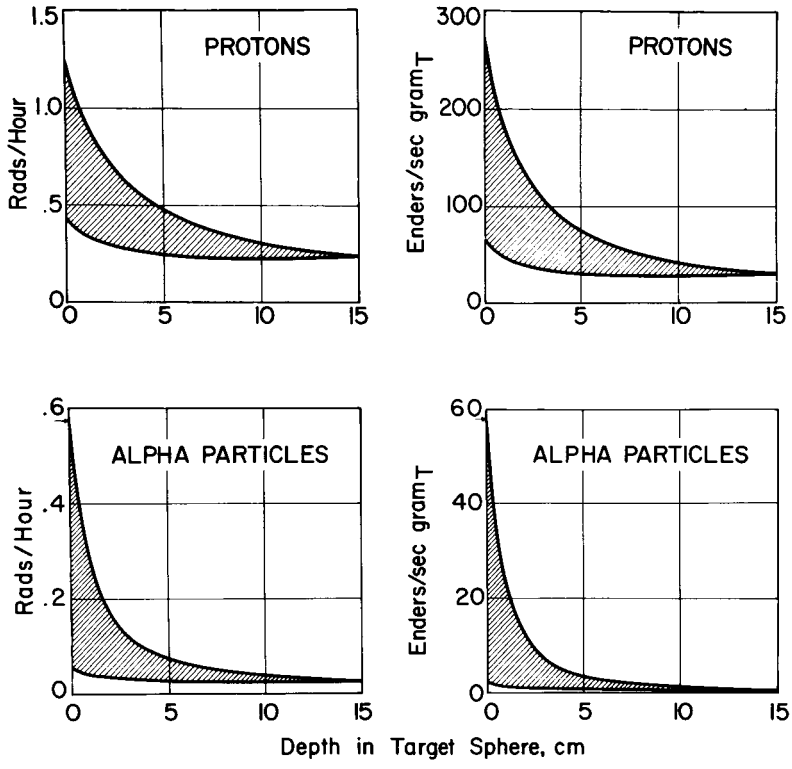

Figure 5

Absorbed Dose and Enders Count in 30 cm Diameter Tissue Sphere in Center of Apollo Command Module for Omnidirectional Incidence of Proton and Alpha Spectra Shown in Figure 3

For conversion of enders/gram tissue to microrads consult Table IV.

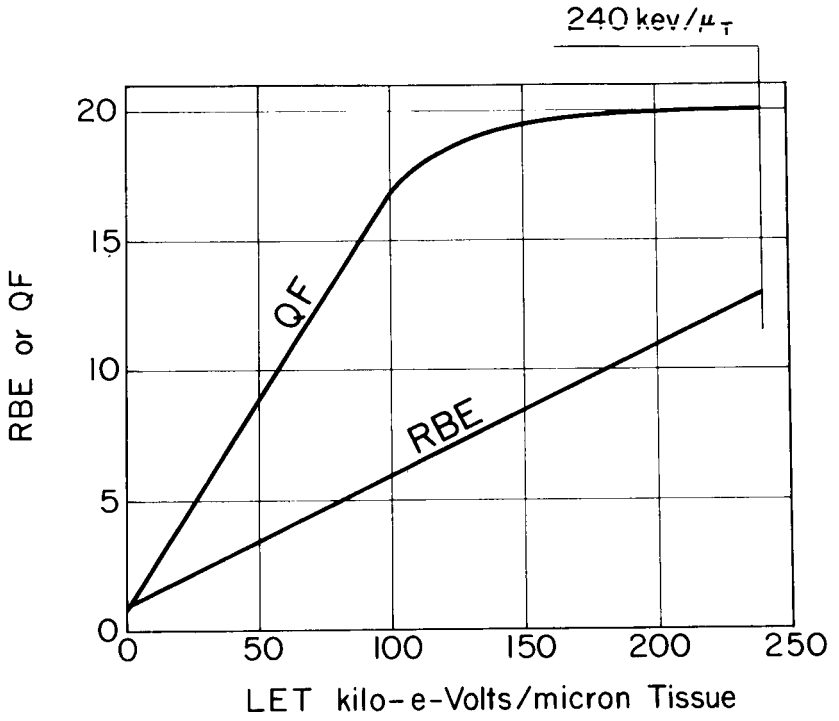

Figure 6

Quality Factor and Relative Biological Effectiveness
as Functions of Linear Energy Transfer

Straight-line sections represent formulae of the RBE Committee. Curvilinear extrapolation of QF beyond 100 kev/micron tissue is arbitrary. (See text for rationale.)

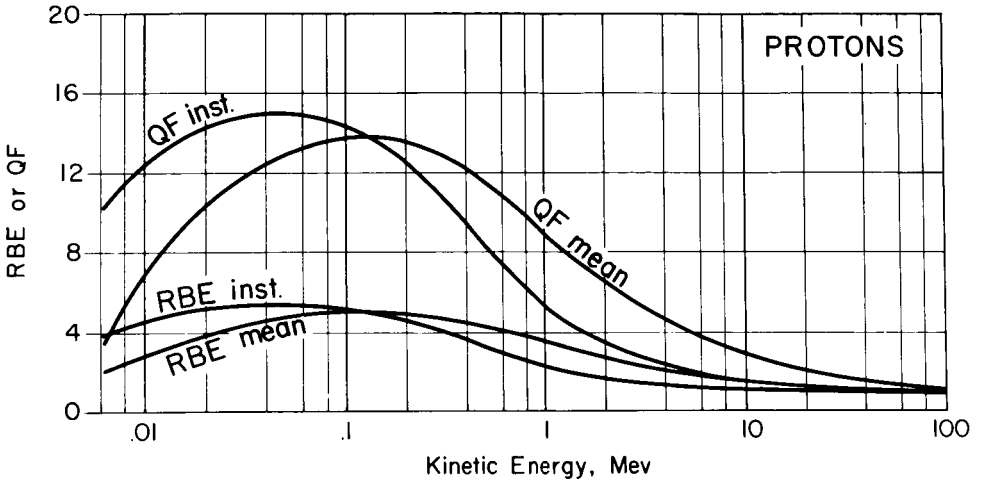

Figure 7

Instantaneous and Mean Quality Factor and Relative Biological Effectiveness as Functions of Kinetic Energy for Protons

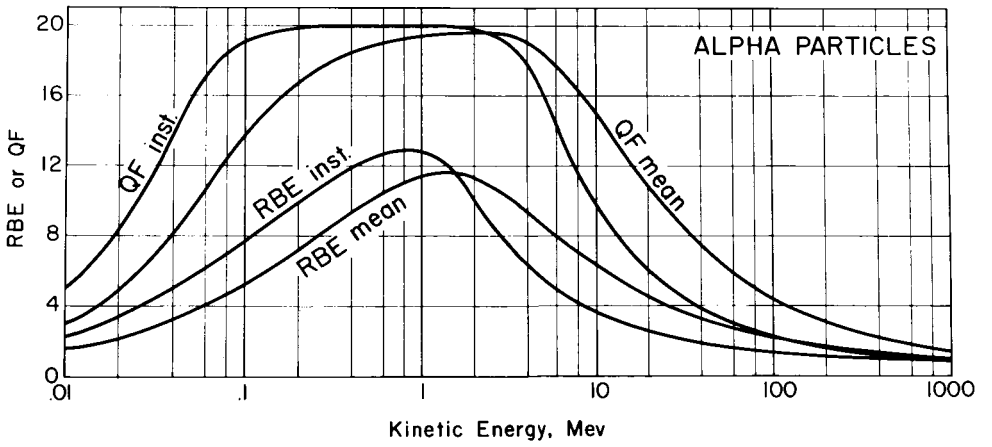

Figure 8

Instantaneous and Mean Quality Factor and Relative Biological Effectiveness as Functions of Kinetic Energy for Alpha Particles

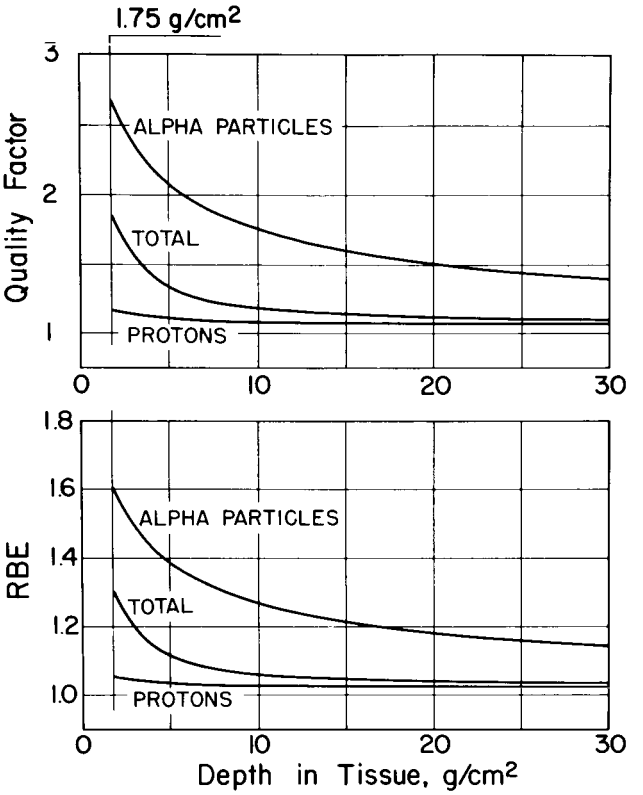

Figure 9

Mean Local Quality Factor and Relative Biological Effectiveness in Tissue for System of Figure 4

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT Depth distributions of absorbed doses and dose equivalents in tissue are computed for the alpha and proton components of a typical rigidity spectrum of a large flare assuming a flux ratio of one to one. Even for the lowest investigated shield thickness of 1.75 g/cm^2 the total alpha dose is smaller than the proton dose and becomes even smaller with depth. The fractional high LET alpha dose, however, is substantially larger than the corresponding proton dose and intersects the latter at 12 g/cm^2 depth in tissue. In spite of this, the combined mean local RBE of the total dose is predominantly determined by the protons. The findings indicate that the alpha component of flare beams creates a significant additional exposure only for cases of very low shielding, such as an astronaut outside the vehicle protected merely by the space suit.

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